

# Theoretical results for top quark processes

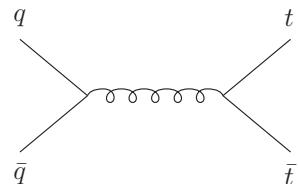
Nikolaos Kidonakis  
(Kennesaw State University)

- $t\bar{t}$  total and differential cross sections
- Single top:  $t$  and  $s$  channels
- $tW^-$  and  $tH^-$  production
- $t\bar{t}W$  and  $t\bar{t}Z$  production
- FCNC processes

## Top-pair production

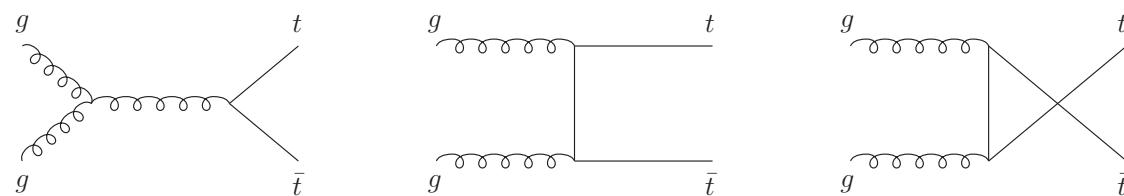
- $q\bar{q} \rightarrow t\bar{t}$

dominant at Tevatron



- $gg \rightarrow t\bar{t}$

dominant at LHC



QCD corrections significant for top pair production

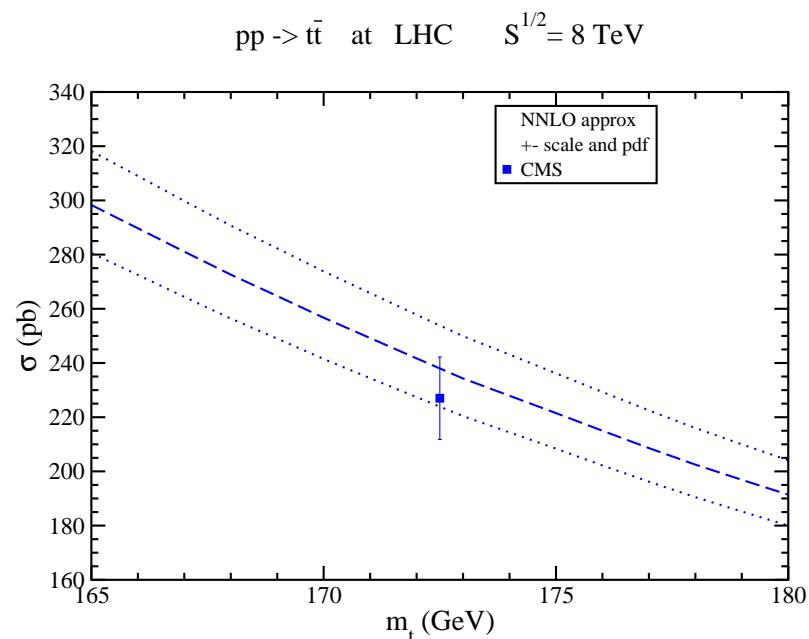
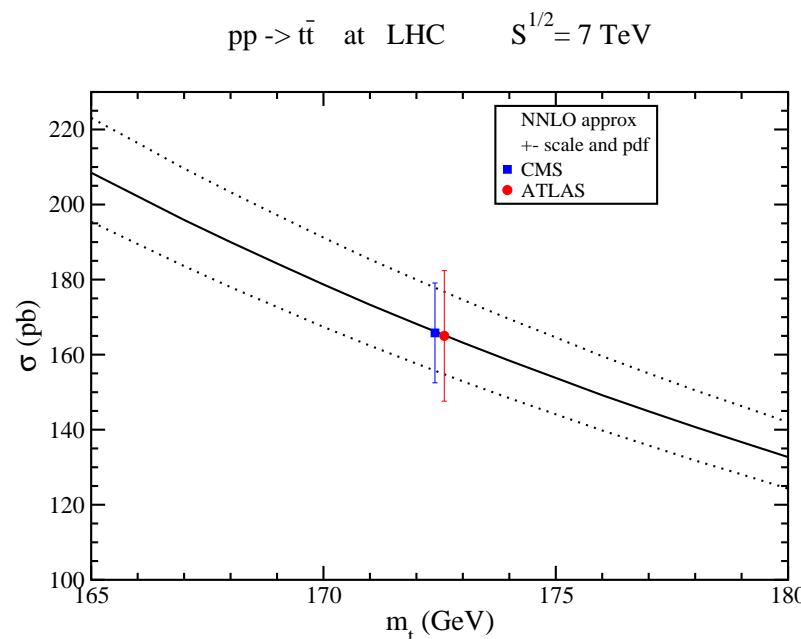
Known fully at NLO (differential) and NNLO (numerical total only)

Soft-gluon corrections are dominant near threshold

NNLL resummation of soft-gluon corrections

NNLO expansions (differential and total)

## $t\bar{t}$ cross section at the LHC



Very good agreement at both 7 and 8 TeV LHC energies

## Differences between various resummation/NNLO approx approaches

### Total vs differential cross section moment-space pQCD vs SCET

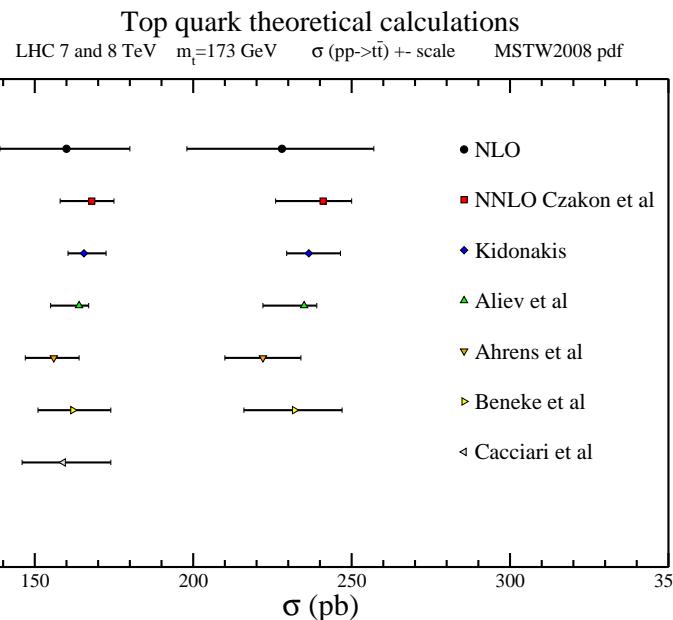
Name	Observable	Soft limit
single-particle-inclusive (1PI)	$d\sigma/dp_T dy$	$s_4 = s + t_1 + u_1 \rightarrow 0$
pair-invariant-mass (PIM)	$d\sigma/dM_{t\bar{t}} d\theta$	$(1 - z) = 1 - M_{t\bar{t}}^2/s \rightarrow 0$
production threshold	$\sigma$	$\beta = \sqrt{1 - 4m_t^2/s} \rightarrow 0$

The more general approach is double-differential  
 $\rightarrow p_T$  and rapidity distributions

total-only approaches are limit/special case (absolute vs partonic threshold)

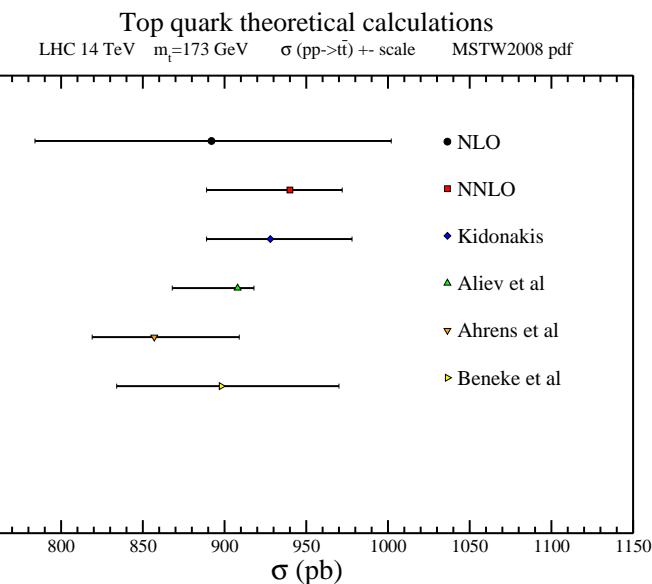
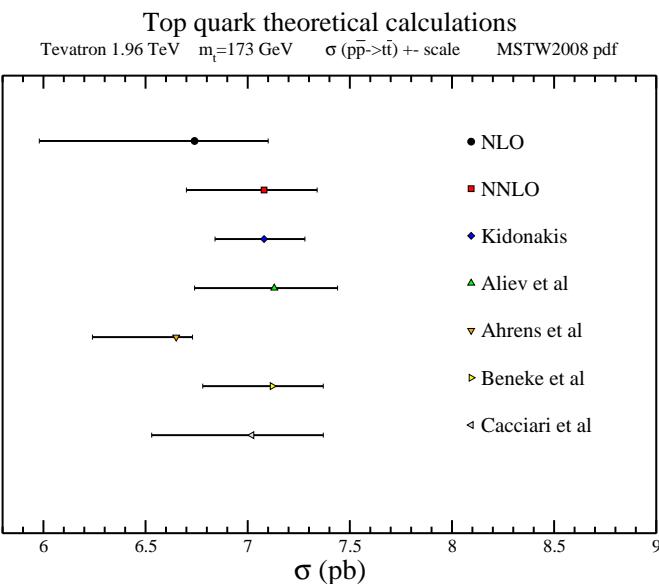
For differential calculations, further differences arise from how the relation  $s + t_1 + u_1 = 0$  is used in the plus-distribution coefficients, how subleading terms are treated, damping factors, etc.

see N. Kidonakis and B.D. Pecjak, Eur. Phys. J C 72, 2084 (2012)  
for details and review



Comparison of various NNLO approx approaches  
all with the same choice of parameters

**Kidonakis, PRD 82, 114030 (2010)** differential-pQCD  
**Aliev et al, CPC 182, 1034 (2011)** total-pQCD  
**Ahrens et al, PLB 703, 135 (2011)** differential-SCET  
**Beneke et al, NPB 855, 695 (2012)** total-SCET  
**Cacciari et al, PLB 710, 612 (2012)** total-pQCD



## Varying degree of success of the various approaches

The Kidonakis PRD 82 result is very close to the exact NNLO:  
both the central values and the scale uncertainty are nearly the same  
true for all collider energies and top quark masses

This was expected from comparison to NLO, and comparison of 1PI  
results at NNLO in 2003

(PRD 68, N. Kidonakis & R. Vogt; see also discussion in PRD78 and PRD82)

less than 1% difference between NLO approximate and exact cross sections  
at both NLO and NNLO

In near future add approximate NNNLO

(see N. Kidonakis PRD 73,034001 (2006) for early NNNLO results)

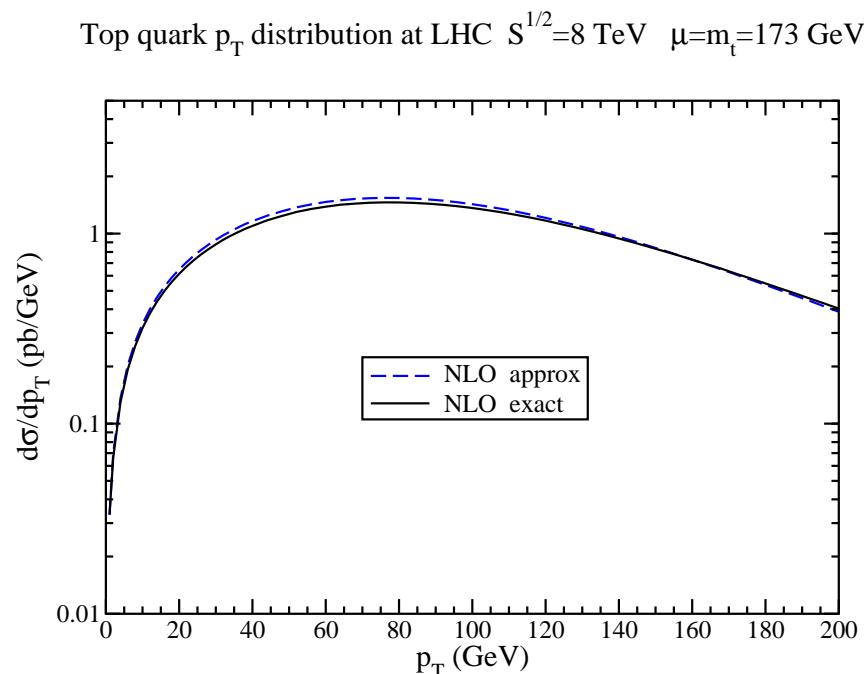
This is the only calculation for partonic threshold at the double differential  
cross section level using the standard moment-space resummation in pQCD  
stability of the theoretical NNLO approx result over the past decade

the reliability of the NNLO approximate result and near-identical value to  
exact NNLO is very important for several reasons

- provides confidence of application to other processes (single-top, W, etc)
- used as background for many analyses (Higgs, etc)
- means that we have near-exact NNLO  $p_T$  and rapidity distributions

## Soft-gluon approximation for distributions

The approximation works very well both for total cross sections and differential distributions



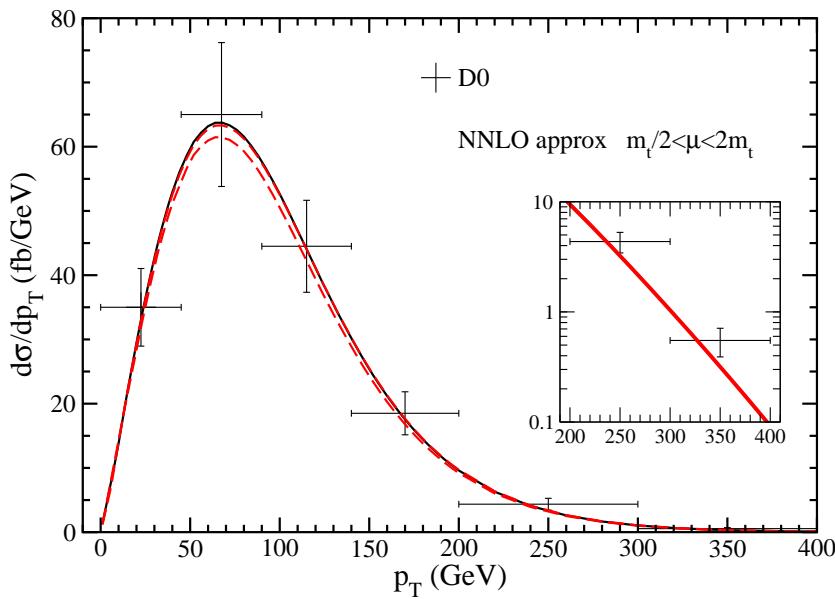
excellent approximation:

1% difference between NLO approximate and exact differential distributions

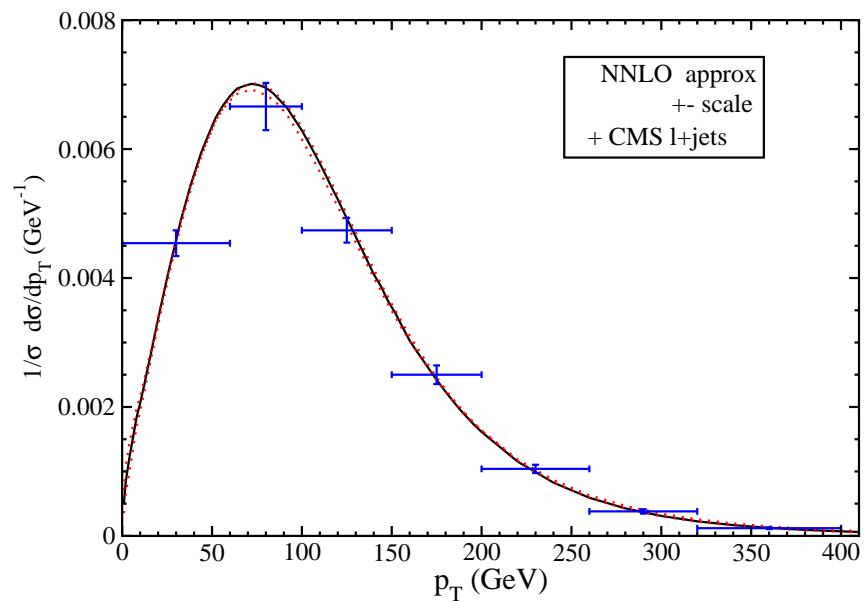
For best prediction add NNLO approx corrections to exact NLO cross section

## Top quark $p_T$ distribution

Top quark  $p_T$  at Tevatron  $S^{1/2}=1.96 \text{ TeV}$   $m=170 \text{ GeV}$

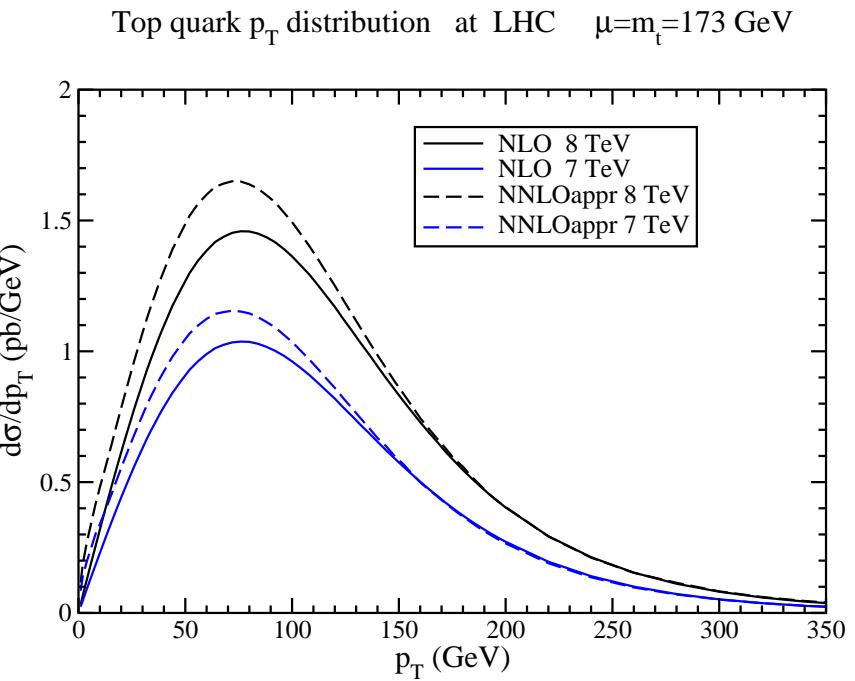
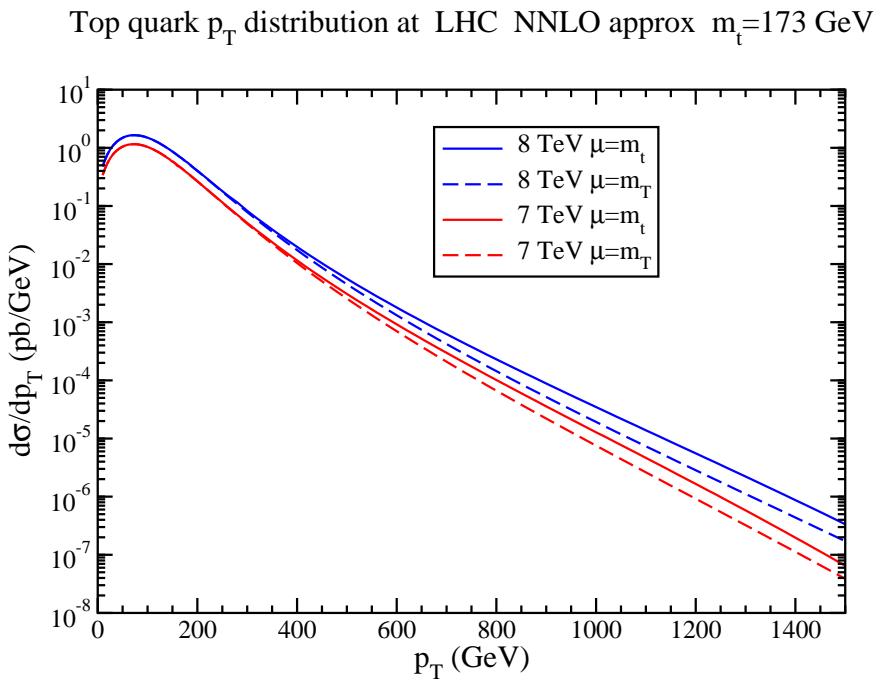


Normalized top  $p_T$  distribution at LHC  $S^{1/2}=7 \text{ TeV}$   $m_t=173 \text{ GeV}$



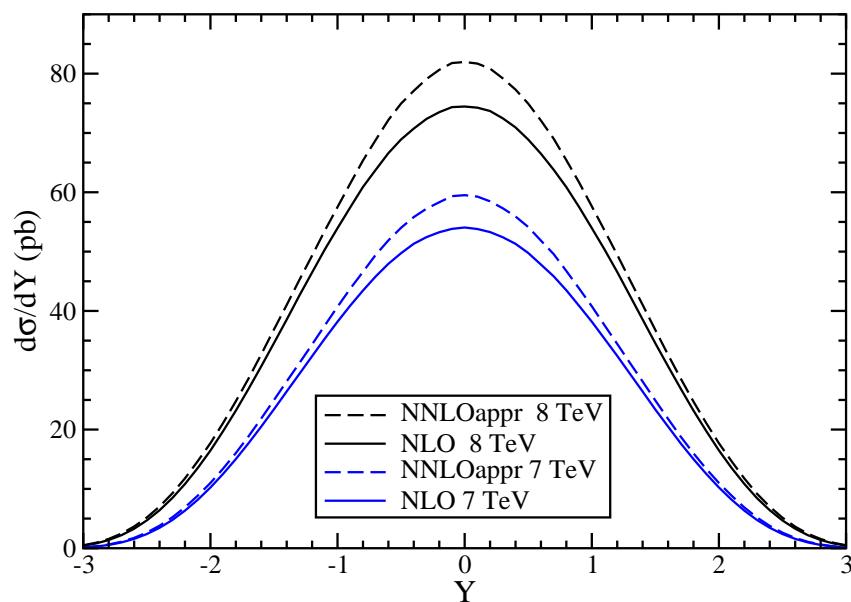
Excellent agreement of NNLO approx results with Tevatron and LHC data

## Top quark $p_T$ distribution at the LHC

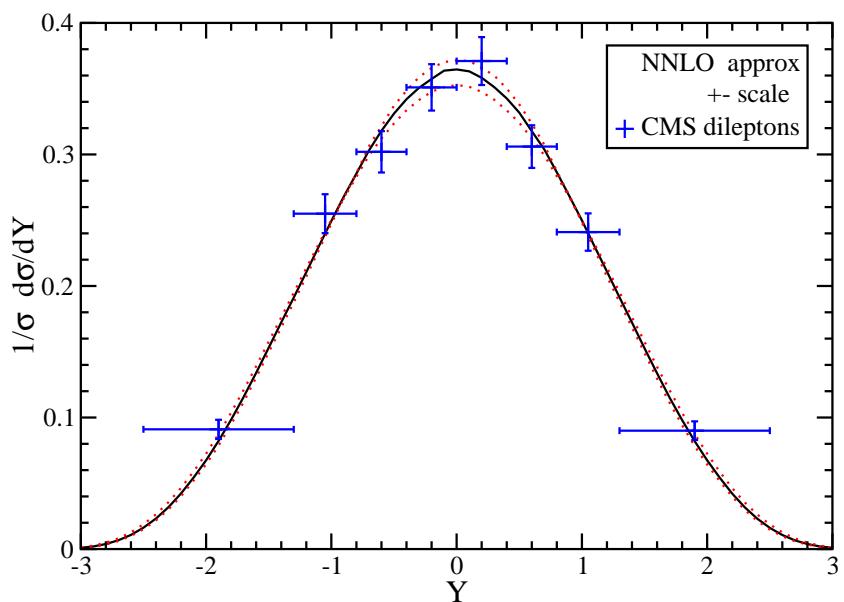


## Top quark rapidity distribution at LHC

Top quark rapidity distribution at LHC  $\mu=m_t=173$  GeV



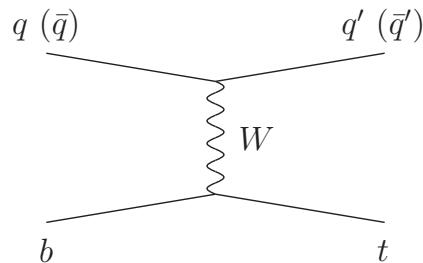
Normalized top  $Y$  distribution at LHC  $S^{1/2}=7$  TeV  $m_t=173$  GeV



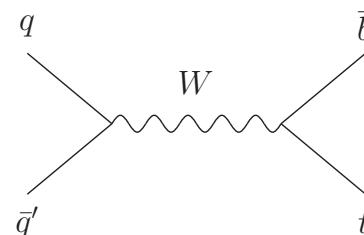
excellent agreement with data

## Single-top partonic processes at LO

- ***t* channel:**  $qb \rightarrow q't$  and  $\bar{q}b \rightarrow \bar{q}'t$   
dominant at Tevatron and LHC

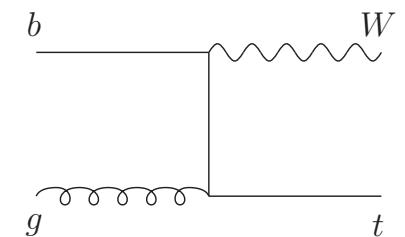
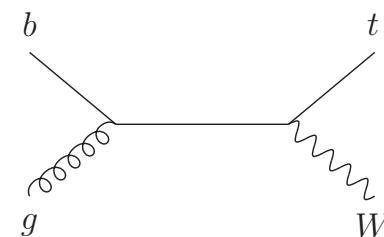


- ***s* channel:**  $q\bar{q}' \rightarrow \bar{b}t$   
small at Tevatron and LHC

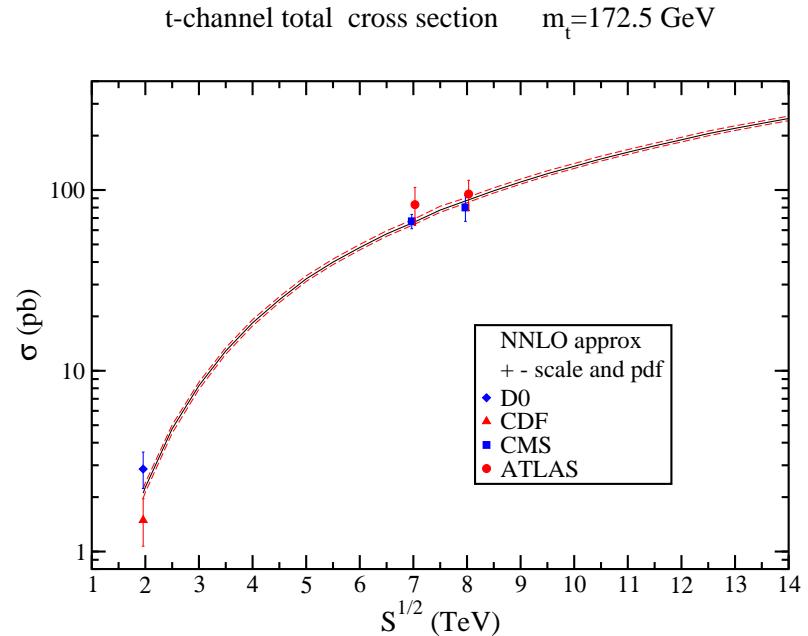
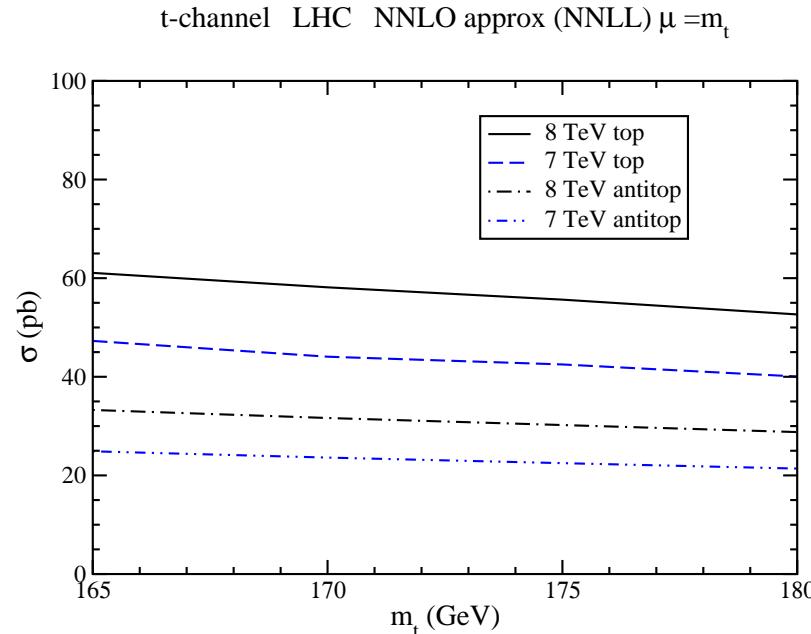


- **associated  $tW$  production:**  $bg \rightarrow tW^-$   
very small at Tevatron, significant at LHC

Related process:  $bg \rightarrow tH^-$



## Single top $t$ -channel cross sections at LHC



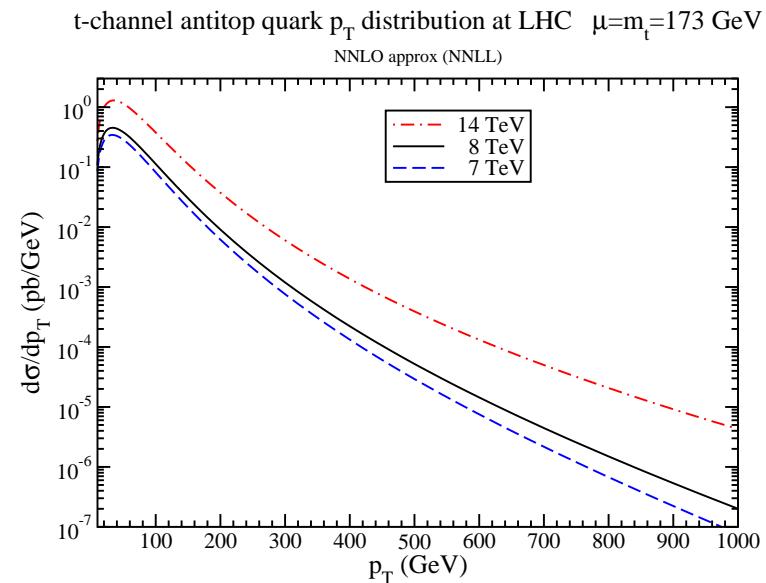
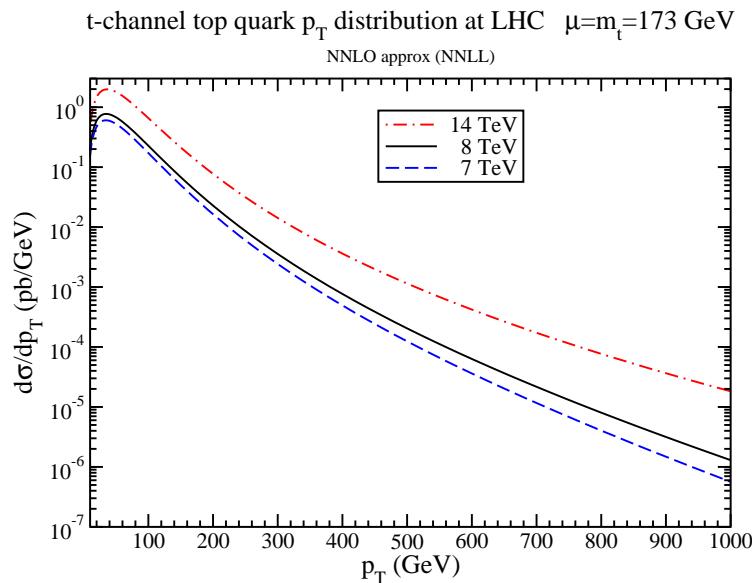
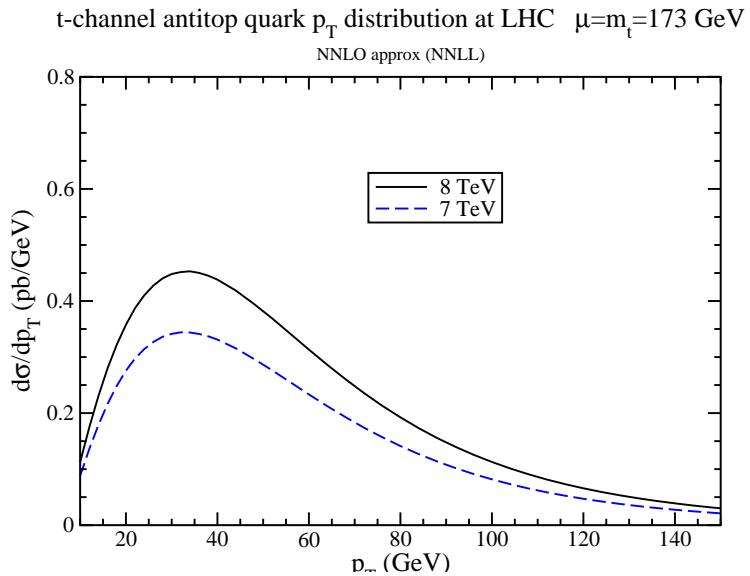
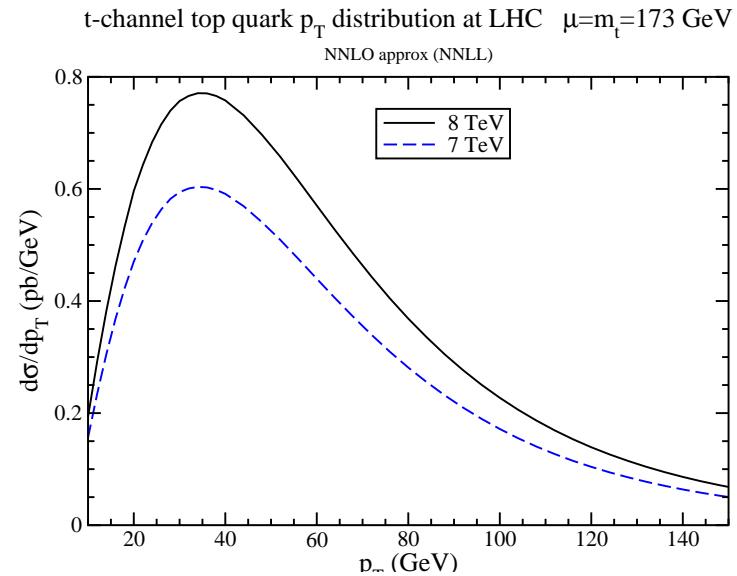
$m_t = 173$  GeV

LHC	$t$	$\bar{t}$	Total (pb)
7 TeV	$43.0^{+1.6}_{-0.2} \pm 0.8$	$22.9 \pm 0.5^{+0.7}_{-0.9}$	$65.9^{+2.1+1.5}_{-0.7-1.7}$
8 TeV	$56.4^{+2.1}_{-0.3} \pm 1.1$	$30.7 \pm 0.7^{+0.9}_{-1.1}$	$87.2^{+2.8+2.0}_{-1.0-2.2}$
14 TeV	$154^{+4}_{-1} \pm 3$	$94^{+2+2}_{-1-3}$	$248^{+6+5}_{-2-6}$

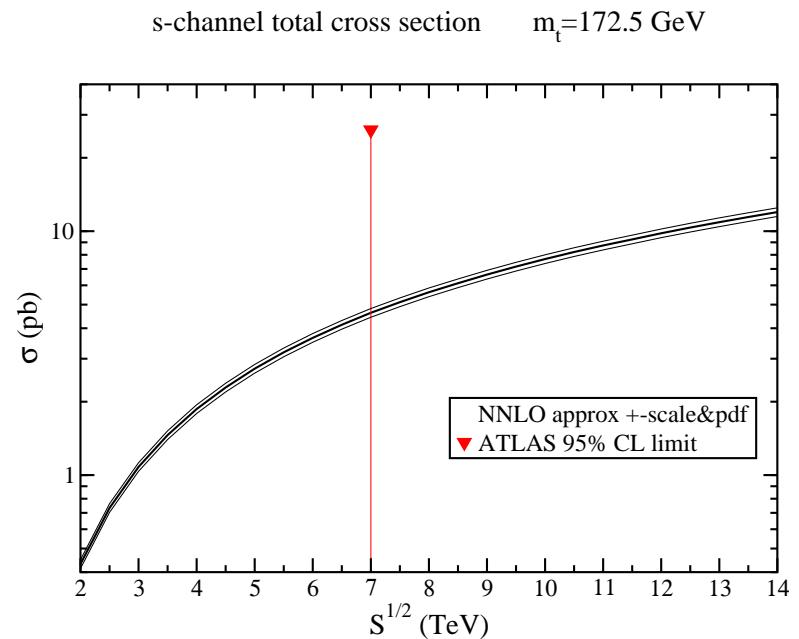
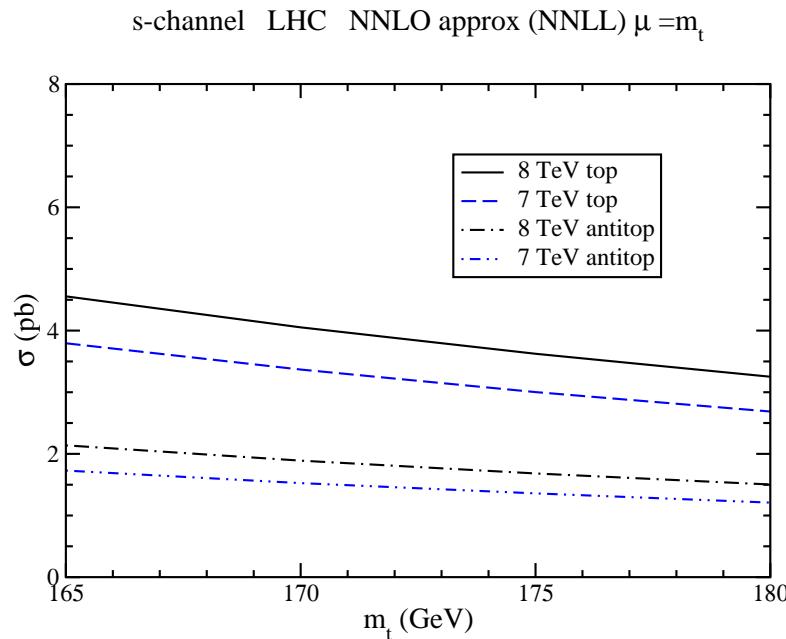
$\pm$  scale  $\pm$  pdf errors with MSTW2008 NNLO pdf 90% CL

ratio  $\sigma(t)/\sigma(\bar{t}) = 1.88^{+0.11}_{-0.09}$  at 7 TeV - compares well with ATLAS result  $1.81^{+0.23}_{-0.22}$

## t-channel top and antitop $p_T$ distributions at LHC



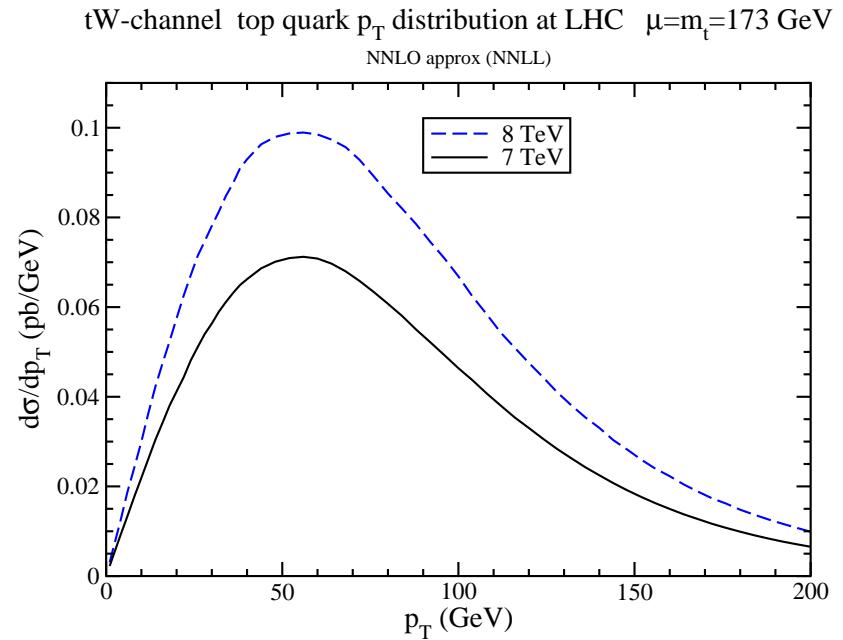
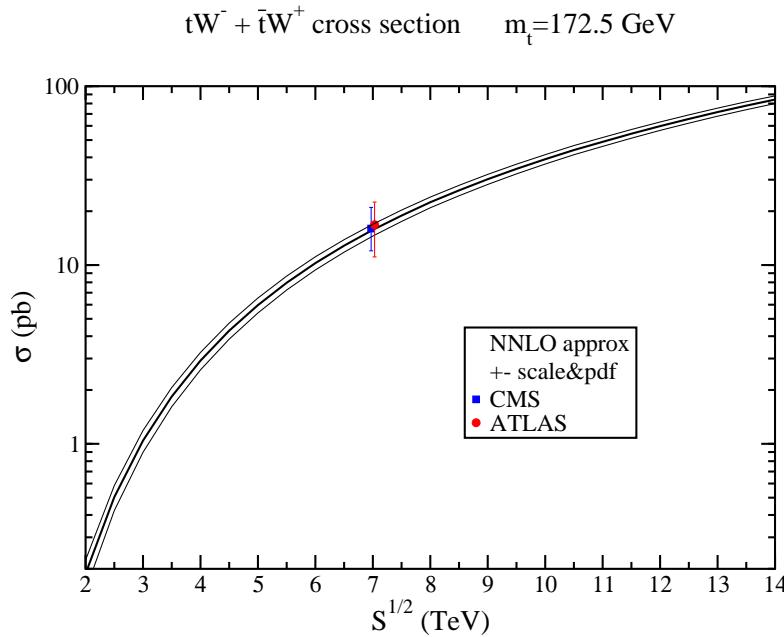
## Single top $s$ -channel cross sections at LHC



LHC	$t$	$\bar{t}$	Total (pb)
$m_t = 173$ GeV	$7$ TeV	$3.14 \pm 0.06^{+0.12}_{-0.10}$	$4.56 \pm 0.07^{+0.18}_{-0.17}$
	$8$ TeV	$3.79 \pm 0.07 \pm 0.13$	$5.55 \pm 0.08 \pm 0.21$
	$14$ TeV	$7.87 \pm 0.14^{+0.31}_{-0.28}$	$11.86 \pm 0.19^{+0.45}_{-0.49}$

NNLO approx: enhancement over NLO (same pdf) is  $\sim 10\%$

## Associated $tW^-$ production at the LHC



$m_t = 173$  GeV

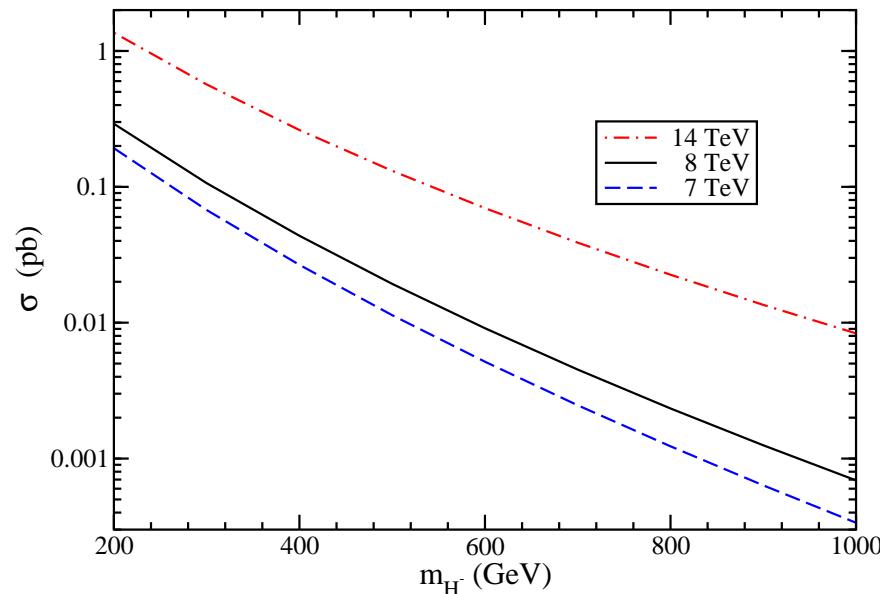
LHC	$tW^-$ (pb)
7 TeV	$7.8 \pm 0.2^{+0.5}_{-0.6}$
8 TeV	$11.1 \pm 0.3 \pm 0.7$
14 TeV	$41.8 \pm 1.0^{+1.5}_{-2.4}$

NNLO approx corrections increase NLO cross section by  $\sim 8\%$

Cross section for  $\bar{t}W^+$  production is identical

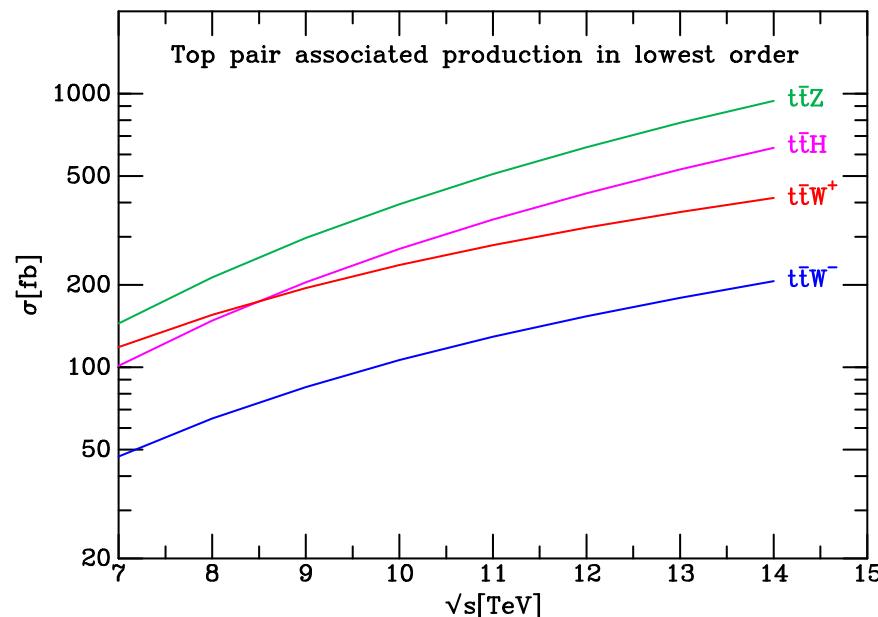
## Associated production of a top quark with a charged Higgs

bg->tH<sup>-</sup> at LHC NNLO approx (NNLL) tanβ=30 μ=m<sub>H<sup>-</sup></sub>



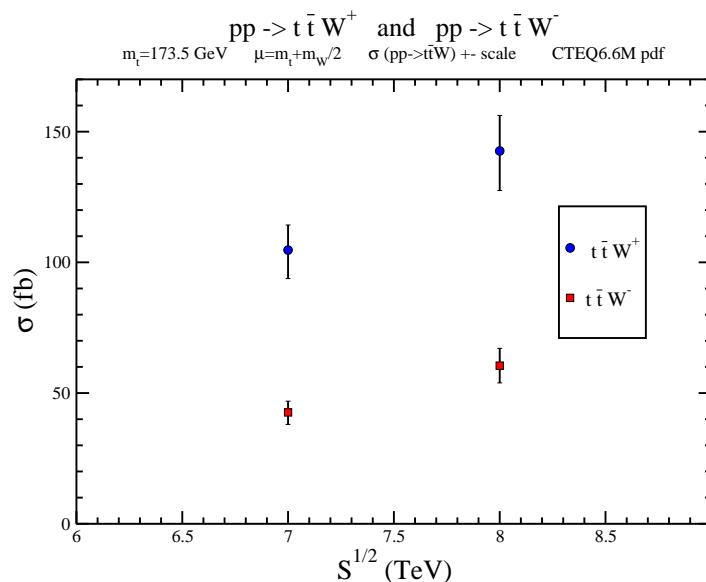
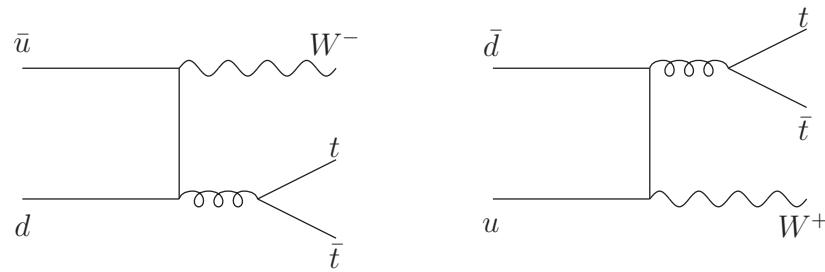
NNLO approx corrections increase NLO cross section by  $\sim 15$  to  $\sim 20\%$

## Associated production of a $t\bar{t}$ pair with bosons



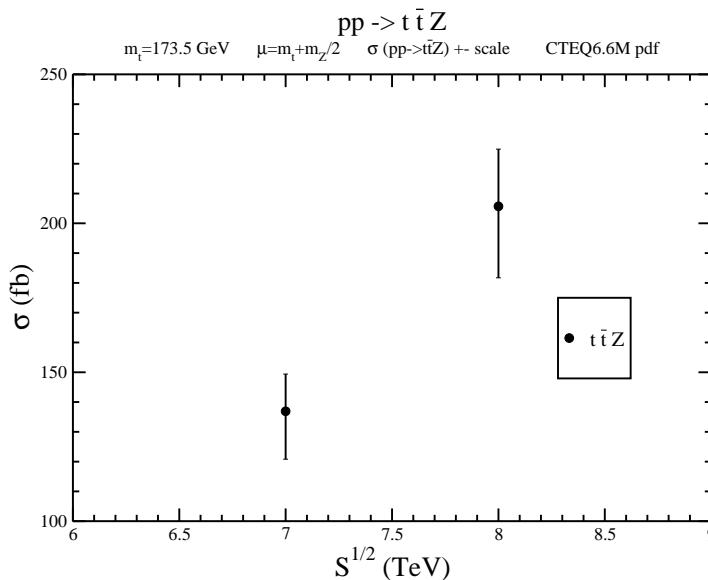
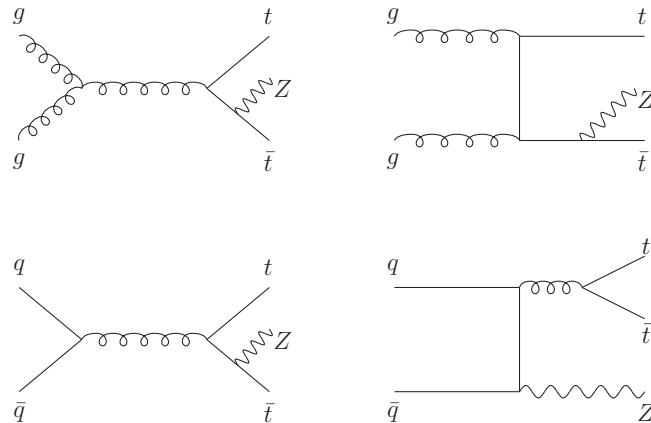
Campbell and Ellis, JHEP 1207 (2012) 052

## $t\bar{t}W$ production



Garzelli, Kardos, Papadopoulos, Trocsanyi, JHEP 1211 (2012) 056

## $t\bar{t}Z$ production



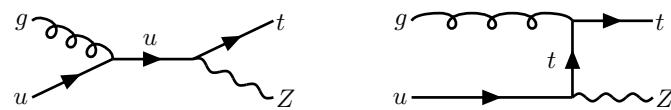
**Garzelli, Kardos, Papadopoulos, Trocsanyi, JHEP 1211 (2012) 056**

## FCNC processes

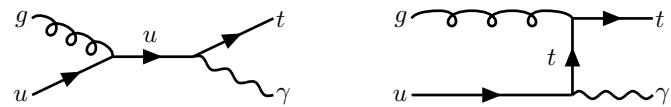
**Single-top production via flavor-changing neutral currents  
Anomalous couplings in Lagrangian, e.g.**

$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda} \kappa_{tqV} e \bar{t} \sigma_{\mu\nu} q F_V^{\mu\nu} + h.c.$$

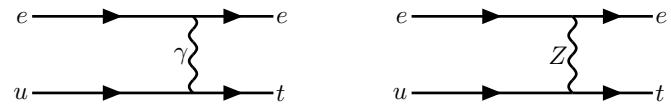
$gu \rightarrow tZ$



$gu \rightarrow t\gamma$



$eu \rightarrow et$



**decrease of scale dependence, significant corrections over LO**

**Future studies at LHC energies and for other couplings**

## Summary

- NNLL resummation / NNLO expansions
- $t\bar{t}$  production cross section
- top quark  $p_T$  and rapidity distributions
- single top cross sections and  $p_T$  distributions
- NNLO approx corrections are very significant
- excellent agreement with LHC and Tevatron data
- $tH^-$  associated production
- top-pair associated production with  $W^+, W^-, Z$
- top quark FCNC processes